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13. ABSTRACT (Maximum 200 words)

In the course of the project, our research has spanned over several areas encompassing theoretical, numerical and phenomenological aspects of stably stratified atmospheric boundary layers (SBLs). We have laid a solid foundation for studying stably stratified turbulence in the framework of a Quasi-Normal Scale Elimination theory (QNSE) developed by us. We consider the QNSE theory as a major breakthrough in this field. Being maximally proximate to the first principles, the theory penetrates very deeply into the physics of anisotropic turbulence and turbulence-wave interaction yet its calculations can be carried out analytically almost to the final results. We have performed initial analytical exploration of the new theory and implemented it in Reynolds-averaged, Navier-Stokes (RANS) models whose predictions agree well with data collected in BASE and SHEBA campaigns. In addition, we investigated non-local features of stable planetary boundary layers (PBLs) caused by semi-organized structures overlooked in traditional boundary-layer meteorology and in PBL schemes currently used in atmospheric models. Theoretical developments focused on basic length scales characterizing semi-organized structures and corresponding revision of classical similarity theory, PBL depth equations, and bulk resistance and heat/mass transfers laws.

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Foreword

In the course of the project, our research has spanned over several areas encompassing theoretical, numerical and phenomenological aspects of stably stratified atmospheric boundary layers (SBLs). We have laid a solid foundation for studying stably stratified turbulence in the framework of a Quasi-Normal Scale Elimination theory (QNSE) developed by us. We consider the QNSE theory as a major breakthrough in this field. Being maximally proximate to the first principles, the theory penetrates very deeply into the physics of anisotropic turbulence and turbulence-wave interaction yet its calculations can be carried out analytically almost to the final results. We have performed initial analytical exploration of the new theory and implemented it in Reynolds-averaged, Navier-Stokes (RANS) models whose predictions agree well with data collected in BASE and SHEBA campaigns. In addition, we investigated non-local features of stable planetary boundary layers (PBLs) caused by semi-organized structures overlooked in traditional boundary-layer meteorology and in PBL schemes currently used in atmospheric models. Theoretical developments focused on basic length scales characterizing semi-organized structures and corresponding revision of classical similarity theory, PBL depth equations, and bulk resistance and heat/mass transfers laws.

Statement of the problem studied

One of the main theoretical goals of this research was an extensive exploration of the physical principles and the promising potential of the new spectral method – the QNSE theory – as applied to stably stratified flows in general and PBLs in particular. Among the most important practical goals was the implementation of the QNSE theory at the level of RANS models; their testing against other models and data and producing practically viable and significantly improved Reynolds stress and/or k-ε models of SBLs.

Other goals included: combining the new models with the models non-local in physical space and validating them via comprehensive comparison with experimental data. Here, the emphasis was put on strong stability regimes, which are basically outside the concern of the classical theories.

Summary of the most important results

The theoretical development of the QNSE theory has been mostly completed. Among other results, it yielded the dispersion relation for internal waves in the presence of turbulence; the internal wave frequency shift, and the criterion of internal wave generation in the presence of turbulence. These results are unique to our theory and, to the best of our knowledge, have been derived analytically for the first time. Various one-dimensional spectra have been calculated analytically and the transition from the Kolmogorov -5/3 regime to the stratification-dominated -3 regime has been confirmed. The coefficient in the N^2k^{-3} regime, rigorously derived in our theory, is in excellent agreement with the one found in LES. In addition, new expressions for horizontal and vertical eddy viscosities and eddy diffusivities, explicitly accounting for the combined effect of turbulence and internal waves, have been obtained.

Although the QNSE theory is quite complicated, its representation of the eddy viscosity and eddy diffusivity are simple enough to be readily implemented in computational schemes. Results of one-column simulations employing the QNSE model-based turbulent mixing parameterizations were tested against the data collected in SBLs over sea ice (BASE and SHEBA campaigns) and shown to exhibit improved accuracy. In parallel, we have investigated non-local features of stably stratified turbulent PBLs caused by semi-organized structures overlooked in the traditional context of boundary-layer meteorology and consequently, in parameterization schemes currently used in climate, weather prediction and meso-scale models. Here, the new theoretical developments addressed basic length scales of turbulence, in particular those characterizing semi-organized structures; advanced diagnostic (equilibrium) and prognostic PBL depth equations; advanced PBL bulk resistance and heat/mass transfers laws expressing the surface fluxes through external parameters. We introduced new concepts of long-lived stable PBLs (as distinguished from the nocturnal, or short-lived PBL, which was the only concern of the traditional theory of stable PBLs) and conventionally neutral PBLs (namely, the PBLs with zero buoyancy flux at the surface developing against stably stratified free atmosphere). Through theoretical analysis supported by LES and experimental studies, we have demonstrated strong effect of the free-flow stability and baroclinicity on the key properties of long-lived stable and conventionally neutral PBLs. This work resulted in principal revision of the essentially local Monin-Obukhov similarity theory, universally accepted over half a century (since 1954). The newly proposed theory accounts for non-local mechanisms driven by semi-organized structures and employs, besides the classical Monin-Obukhov length scale, the free-flow stability scale and the rotational scale. These developments open new opportunities for improved parameterization of stable PBLs in a range of environmental models. Recall that the Monin-Obukhov similarity theory underlies all surface-flux parameterization schemes currently employed in operational models, which causes considerable errors in calculations of surface fluxes in strongly stable stratification (this problem was emphasized in the recent NOAA report on the present state of atmospheric modeling).

Among other fundamental and innovative results from this project is the conclusion about the absence of the critical Richardson number. On the one hand, this result follows directly from the QNSE theory; on the other, a new, non-local surface layer model developed in this study have explained why and how developed turbulence is maintained close to the surface at very large ("supercritical") Richardson numbers.

We have also explored analogies between internal waves and Rossby waves and between horizontal layering and generation of systems of quasi-one-dimensional zonal jets in flows dominated by stable stratification and beta-effect, respectively.

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(6) Listing of all publications supported under this grant

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(7) List of participating scientific personnel (showing advanced degrees earned while employed on the project)

Boris Galperin – University of South Florida
Semion Sukoriansky – Ben-Gurion University of the Negev, Israel
Nadejda Dikovskaya, Post-doctoral fellow, Ben-Gurion University of the Negev, Israel

Veniamin Perov – Swedish Meteorological and Hydrological Institute, Sweden
Sergej Zilitinkevich - started working in this project while being Professor and Chair of Meteorology and Head of MIUU (Meteorology Institute, Uppsala University). On 1 July 2004 became Professor Emeritus at Uppsala University. In 2004 was awarded the Marie Curie Chair of Boundary-Layer Physics and now is affiliated with the Department of Physical Sciences, University of Helsinki, Finland.